The Primordial Abundance of ^{6}Li and ^{9}Be

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ABSTRACT

Light element (^{6}Li, ^{7}Li and ^{9}Be) depletion isochrones for halo stars have been calculated with standard stellar evolution models. These models include the latest available opacities and are computed through the sub-giant branch. If ^{6}Li is not produced in appreciable amounts by stellar flares, then the detection of ^{6}Li in HD 84937 by Smith, Lambert & Nissen (1993) is compatible with standard stellar evolution and standard big bang nucleosynthesis only if HD 84937 is a sub-giant. The present parallax is inconsistent with HD 84937 being a sub-giant star at the $2.5\,\sigma$ level. The most metal poor star with a measured ^{9}Be abundance is HD 140283, which is a relatively cool sub-giant. Standard stellar evolution predicts that ^{9}Be will have been depleted in this star by ~ 0.3 dex (for $T_{\rm eff} = 5640$ K). Revising the abundance upward changes the oxygen-beryllium relation, suggesting incompatibility with standard comic ray production models, and hence, standard big bang nucleosynthesis. However, an increase in the derived temperature of HD 140283 to 5740 K would result in little depletion of ^{9}Be and agreement with standard big bang nucleosynthesis.

Subject headings: early universe – nucleosynthesis – stars: interiors – stars: abundances

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1. Introduction

The primordial abundance of the light elements provide a crucial test of standard big bang nucleosynthesis (SBBN) theory. In SBBN, the abundances of the light elements are functions of the baryon to photon ratio in the early universe. SBBN does not produce appreciable amounts of ^{6}Li, or any element heavier than ^{7}Li. Consistency with the inferred primordial abundance of ^{4}He and (D + ^{3}He) requires that the baryon to photon ratio (η) lies in the narrow range $2.86 \times 10^{-10} \leq \eta \leq 3.77 \times 10^{-10}$ and implies that the primordial ^{7}Li abundance should be $1.9 \leq \log \mathrm{N(Li)} \leq 2.4$ (Smith, Kawano & Malaney 1993, where $\log \mathrm{N(Li)} = \log(\mathrm{Li/H}) + 12$). The primordial ^{4}He abundance is restricted to the range $0.237 \leq Y_p \leq 0.247$. Various alternative to SBBN have been proposed, some of which predict significantly different values for the primordial ^{6}Li, ^{7}Li and ^{9}Be abundances (cf. the review by Malaney & Mathews 1993). An accurate determination of the primordial light element abundances has important implications for particle physics and cosmology. However, ^{6}Li, ^{7}Li and ^{9}Be are fragile elements which can be destroyed within stars. In addition, these elements may be produced by cosmic rays in the early galaxy. It has also been suggested that stellar flares may produce observable amounts of ^{6}Li in stars which contain very thin convective envelopes (Smith, Lambert & Nissen 1993, hereafter SLN93; Deliyannis & Malaney 1994) In order to relate the presently observed abundances to their primordial value, it is important to study possible depletion/production mechanisms which occur after the big bang.

The observed abundances of the light elements in halo stars[1] provide our best starting point for determining the primordial abundances, as these low metallicity stars are the least affected by post big bang production mechanisms. It was originally shown by Spite & Spite (1982) that halo stars with effective temperatures greater than 5700 K have a nearly uniform Li abundance[2]. The consistency of the Li abundance in hot halo stars was confirmed by other observations (eg. Spite & Spite 1986; Hobbs & Thorburn 1991). The observed Li abundance ($\log \mathrm{N(Li)} \simeq 2.1$) is consistent with the predictions of SBBN ($1.9 \leq \log \mathrm{N(Li)} \leq 2.4$, Smith *et al.* 1993). In standard stellar evolution theory the only way in which the observed surface value of a light element would be depleted is if the convection zone is deep enough to dredge up material which has destroyed the light element. Detailed modeling by Deliyannis, Demarque & Kawaler (1990) demonstrated that the convection zones in old, metal poor stars are too shallow to dredge up substantial amounts of ^{7}Li depleted material, hence the observed ^{7}Li abundance does indeed reflect the primordial value (provided post big bang enrichment is neglible). However, if mixing occurs within the radiative region of a star, then substantial ^{7}Li depletion may occur. Models which include diffusion find primodial ^{7}Li abundances 0.2 dex higher than standard models (Deliyannis *et al.* 1990; Proffitt & Michaud 1991; Chaboyer & Demarque 1994). Instabilities induced by rotation may also mix material in stellar radiative regions. Models which include rotation induced mixing found ^{7}Li depletion of ~ 0.9 dex, and imply a primordial ^{7}Li abundance incompatible with SBBN (Pinsonneault, Deliyannis, & Demarque 1992; Chaboyer & Demarque 1994).

The predictions of SBBN may be put to a more stringent test if we consider other light elements. ^{9}Be has been observed in a substantial number of stars (eg. Gilmore *et al.* 1992, hereafter GGEN92; Boesgaard & King 1993, hereafter BK93), while B has been observed in a few stars (Duncan, Lambert & Lemke 1992; Edvardsson *et al.* 1994). These elements require substantially higher temperatures to be destroyed, and so are less likely to be depleted in stellar interiors. SLN93 have recently claimed to have detected ^{6}Li in a single halo star, HD 84937. This detection awaits confirmation, but it is assumed here that the detection is real. This *Letter* will examine the light element depletions predicted by standard stellar evolution and compare them to the observations.

2. Li Depletion Isochrones

Light element depletion in halo stars has been studied by Deliyannis *et al.* (1990); Proffitt & Michaud (1991); Deliyannis & Demarque (1991) and Pinsonneault, Deliyannis & Demarque (1992). The primary difference between the standard models pre-

[1] The term halo star is used to denote extremely metal poor stars ([Fe/H] < -1.0), which are likely to be the oldest stars in our galaxy.

[2] Observers are usually not able to measure the isotopic abundance of Li, so they measure the total Li content in a star, which we denote by Li. However the theoretical calculations predict considerably different production/depletion for the two stable Li isotopes, ^{6}Li and ^{7}Li, and so our discussion of theoretical work will retain the distinction between ^{6}Li and ^{7}Li.

sented here, and those in earlier studies is the opacity used in the models. The present models use the opacities of Iglesias & Rogers (1991) for high temperatures and Kurucz (1991) opacities for temperatures below 10^4 K. Previous work used opacities from Cox & Stewart (1970), or Huebner *et al.* (1977). The new opacities are substantially enhanced over the old values in certain temperature, density regimes which leads to deeper convection zones in most of the models.

An extensive grid of standard stellar models, with $\mathrm{M} = 0.55\ \mathrm{M}_\odot - 0.82\ \mathrm{M}_\odot$ (in 0.01 $\mathrm{M}_\odot$ intervals) and $\mathrm{Z} = 10^{-3}$, 10^{-4} and 10^{-5} has been constructed in order to study the light element depletion in halo stars. These models are evolved from the fully convective pre-main sequence to an age of 18 Gyr, or through the sub-giant phase of evolution, whichever occurred first. Full details of the model construction may be found in Chaboyer & Demarque (1994). These models were used to construct light element destruction isochrones with ages of 14 and 17 Gyr, chosen to span the typically age range observed in the halo (eg. Chaboyer, Sarajedini, & Demarque 1992). These isochrones are available in electronic form from the author. Chaboyer & Demarque (1994) compared the ^{7}Li isochrones to the observations and found good agreement with the observations of Thorburn (1994) implying a primordial ^{7}Li abundance of $\log \mathrm{N(Li)} = 2.24 \pm 0.03$.

The Li destruction isochrones are presented in Figure 1 for $t = 17$ Gyr, $Z = 10^{-4}$. Above $\sim$ 5900 K, the ^{6}Li depletion is constant on the *sub-giant branch*, with a depletion factor (defined as $\mathrm{D} \equiv\ ^6\mathrm{Li}/^6\mathrm{Li}_{\mathrm{protostellar}}$) of approximately 0.3. However, no such depletion plateau occurs for ^{6}Li on the main sequence. The predicted abundance of ^{6}Li is a strong function of effective temperature on the main sequence. The sub-giant ^{7}Li isochrone is a nearly constant offset from the sub-giant ^{6}Li sub-giant isochrone. Thus, the standard models predict observations of the $^6\mathrm{Li}/^7\mathrm{Li}$ ratio should be constant over a wide range of effective temperatures in halo sub-giant stars.

The light element depletion isochrones are sensitive to the mixing length used in the models (Deliyannis *et al.* 1990). The models presented here use a solar calibrated mixing length ($\alpha = 1.728$). These models were used to construct isochrones, and compared to the colour-magnitude diagram of M15 (Durrell & Harris 1993), a metal-poor globular cluster. Conversion from the theoretical temperature-luminosity plane to the observed colour-magnitude plane was performed using both the Green (1988) colour calibration and the Kurucz (1991) colour calibration. Both sets of isochrones are a good fit[3] to the observations. Hence, the effective temperatures derived from the models are in good agreement with globular cluster observations. Stellar models and isochrones were also constructed with mixing lengths of $\alpha = 1.5$ and 2.0. It was found that most of these isochrones did not match the colour magnitude of M15, indicating that the solar calibrated mixing length is the appropriate one to use for halo stars. However, the $\alpha = 2.0$ isochrone with the Kurucz colour calibration did provide a satisfactory fit. This suggests that the effective temperatures predicted by the stellar models are accurate to within $\sim$ 80 K on the main sequence and sub-giant branches.

Fig. 1.— Standard Li destruction isochrones at age of 17 Gyr with $Z = 10^{-4}$ on the main sequence and during sub-giant evolution. The vertical axis is defined as $\log \mathrm{D} \equiv \log(\mathrm{Li}/\mathrm{Li}_{\mathrm{protostellar}})$. The two lower lines are for ^{6}Li, while the two upper lines are for ^{7}Li.

3. The Case of HD 84937

To date, ^{6}Li has been claimed to be detected in a single halo star – HD 84937 by SLN93. They determined $^6\mathrm{Li}/^7\mathrm{Li} = 0.05 \pm 0.02$ and $\log \mathrm{N(Li)} = 2.12$. In this *Letter* the actual $^6\mathrm{Li}/^7\mathrm{Li}$ ratio in HD 84937 is assumed to lie in the range $0.03 - 0.07$. SLN93

[3] In performing the isochrones fits, the reddening and distance modulus were allowed to vary within twice the quoted errors of Durrell & Harris (1993). A fit was deemed satisfactory if the isochrones were able to simultanesouly match the location of the lower main sequence and sub-giant/giant branches.

determined the metallicity to be [Fe/H] $= -2.4$ and $T_{\rm eff} = 6090 \pm 100$ K. This is ~ 100 K lower than other estimates for this star. For example, Thorburn (1994) determined an effective temperature of 6232 ± 100 K for this star. King (1993) advocates a higher temperature scale for halo stars, and finds $T_{\rm eff} = 6312$. We will assume that the effective temperature of HD 84937 lies in the region $6000 - 6300$ K. The evolutionary status of HD 84937 is also somewhat uncertain. Strömgren photometry locates HD 84937 at the bluest point of the turnoff (SLN93). However, the effective temperature of this star is too low for it to be a massive main sequence star. Stellar models with the metallicity of HD 84937 typically have turn-off temperatures ranging from 6700 K (age 14 Gyr) to 6540 K (age 18 Gyr). SLN93 suggest that HD 84937 is a sub-giant, however it is possible that HD 84937 is a lower mass main-sequence star. We will consider both possibilities in the discussion which follows.

Our $Z = 10^{-4}$ isochrone corresponds to [Fe/H] $=$ -2.55 and $[\alpha/\mathrm{Fe}] = +0.40$ (assuming that the effects of α-element enhancement may be accounted for by modifying the overall Z of the star, as outlined by Salaris, Chieffi & Straniero 1993) and so is the most appropriate isochrone to compare to the observation. If HD 84937 is a main sequence star, then the models predict that the protostellar ^{6}Li has been depleted by a factor of 13 ($T_{\rm eff} = 6300$ K) to 250 ($T_{\rm eff} = 6000$ K). The ^{7}Li is not depleted in the models over this effective temperature range. Hence, if HD 84937 is a main sequence star, then the *protostellar* $^6\mathrm{Li}/^7\mathrm{Li}$ ratio is in the range $0.40 - 17$. This requires a large primordial abundance of ^{6}Li or substantial cosmic ray production of ^{6}Li. The $^6\mathrm{Li}/^7\mathrm{Li}$ ratio produced by cosmic rays is approximately one, thus production of large amounts of ^{6}Li by cosmic rays would produce substantial amounts of ^{7}Li. This would lead to a correlation between metallicity and Li abundance in the halo stars, which is not observed. Thorburn 1994 finds a correlation which is a factor of 2 too small to account for a protostellar $^6\mathrm{Li}/^7\mathrm{Li}$ ratio of 0.40. Thus, consistency with SBBN and standard stellar evolution models implies that HD 84937 is not a main sequence star. In analysing the ^{6}Li detection in HD 84937, Steigman *et al.* (1993) arrived at the opposite conclusion, namely that the detection was consistent with standard models, even if HD 84937 is a main sequence star. The difference between Steigman *et al.* (1993) and this work is that Steigman *et al.* (1993) used the standard stellar models of Deliyannis *et al.* (1990) which deplete less ^{6}Li then the models presented here. In addition, Steigman *et al.* (1993) allowed for a much larger error in the observed ^{6}Li abundance.

If HD 84937 is a sub-giant, then the situation is considerably different. For effective temperatures between 6000 and 6300 K, the sub-giant models predict that ^{6}Li is depleted by a factor of 2.8, while virtually no depletion of ^{7}Li occurs. This relatively mild amount of ^{6}Li depletion implies that the protostellar $^6\mathrm{Li}/^7\mathrm{Li}$ ratio is in the range $0.084 - 0.20$. This range is consistent with SBBN (which produces no ^{6}Li) and production of ^{6}Li and ^{7}Li (in roughly equally proportions) by cosmic rays. Thus, the observations are consistent with SBBN, provided that HD 84937 is a sub-giant. The parallax of HD 84937 is $0.0277'' \pm 0.0065''$ (van Altena, Lee & Hoffleit 1994). If HD 84937 is a sub-giant, then the models predict a minimum absolute V magnitude of $M_V = 3.56$ (corresponding to a 17 Gyr sub-giant with $T_{\rm eff} = 6300$ K). The apparent V magnitude of HD 84937 is observed to be $V = 8.32$ (Stetson & Harris 1988). This implies a parallax of 0.0112, which is $2.5\,\sigma$ smaller than observed. If HD 84937 is a main sequence star, then the models predict a parallax ranging from $0.0205''$ to $0.0273''$, which agrees with the observed value. We caution however, that measurement of a parallax is a difficult observations, and so the true error in the parallax may be higher than the quoted value. An improved determination of the parallax (possible with HIPPARCOS) would be able to answer the question of the evolutionary status of HD 84937, and so would serve as a test of the 'standard model' (standard stellar evolution, no production of ^{6}Li by stellar flares, standard production of light elements via cosmic rays, and SBBN).

4. ^{9}Be Destruction Isochrones

The ^{9}Be destruction isochrones in standard models are shown in Figure 2 for $Z = 10^{-4}$ (the $Z = 10^{-5}$ and $Z = 10^{-3}$ isochrones are virtually identical). No ^{9}Be destruction occurs on the main sequence, but ^{9}Be destruction occurs on the sub-giant branch when $T_{\rm eff} \lesssim 5750$ K. This can have important implications for the interpretation of ^{9}Be observations. For example, the most metal poor star observed is HD 140283 with [Fe/H] $= -2.77$ (GGEN92). GGEN92 determined a ^{9}Be abundance of $\log\,(N_{\rm Be}/N_{\rm H}) = -12.97 \pm 0.25$ and quote $T_{\rm eff} = 5540$ K, $\log g = 3.5$. BK93 find $\log\,(N_{\rm Be}/N_{\rm H}) = -12.78 \pm 0.14$, $T_{\rm eff} = 5660$ K and $\log g = 3.6$. Ryan *et al.* (1992) obtained

Fig. 2.— Standard ^{9}Be destruction isochrones at age of 17 Gyr with $Z = 10^{-4}$ on the main sequence and during subgiant evolution. ^{9}Be destruction occurs for sub-giants with $T_{\rm eff} \lesssim 5700$ K.

$\log(N_{\rm Be}/N_{\rm H}) = -13.25 \pm 0.4$ with $T_{\rm eff} = 5700$ K, and $\log g = 3.2$. These effective temperatures and gravities imply that HD 140283 is a sub-giant, which has depleted ^{9}Be according to standard stellar evolution models. The amount of ^{9}Be depletion in stellar models is extremely sensitively to the assumed effective temperature. The depletion factor is 0.46 dex at $T_{\rm eff} = 5585$ K, 0.2 dex at $T_{\rm eff} = 5660$ K and 0.1 dex at 5700 K. Thus, the protostellar ^{9}Be abundance in HD 140283 inferred from the observations is $\log(N_{\rm Be}/N_{\rm H}) = -12.51$, -12.58 and -13.15 (GGEN92, BK93, and Ryan *et al.* 1992 respectively).

Revising the ^{9}Be abundance of HD 140283 upward changes the oxygen-beryllium relation, as HD 140283 is the most metal poor star observed. The abundance of ^{9}Be in other metal poor stars is not affected, as these stars are hotter than HD 140283. If we use the GGEN92 or BK93 abundance, then HD 140283 would have a similar or higher ^{9}Be abundance than HD 213657, HD 106617 and HD 116064 which have oxygen abundances 0.4 dex higher than HD 140283. This suggests that there may exist a plateau in the ^{9}Be abundance at low metallicity, implying a primordial origin to the ^{9}Be. This is incompatible with SBBN. A least squares analysis of the O–^{9}Be data of GGEN92 for stars with $[{\rm O/H}] \leq -1.0$ yields a correlation coefficient of 0.57, and a slope of 0.5. This slope is inconsistent with the simple cosmic ray production models of GGEN92 which predict a slope of 1 – 2.

The low ^{9}Be abundance found by Ryan *et al.* (1992) is compatible with simple cosmic ray production models (e.g. Steigman *et al.* 1993). If the actual temperature of HD 140283 is $T_{\rm eff} \gtrsim 5740$ K, then no ^{9}Be depletion is predicted in the standard stellar evolution models, and agreement is found with SBBN. King (1993) advocates a higher effective temperature scale for halo stars, and determines $T_{\rm eff} = 5812$ K for HD 140283. At such temperatures, no ^{9}Be depletion is predicted by standard stellar evolution models, and evidence for a plateau in the ^{9}Be abundance is weakened. As noted earlier, there is a possible error of ~ 80 K in the models. Thus, the exact amount of ^{9}Be depletion in cool sub-giants is somewhat uncertain. Observing stars which are hotter than $T_{\rm eff} = 5800$ K removes this uncertainty.

Edvardsson *et al.* (1994) have measured the B abundance in HD 140283 to be $\log\,(N_{\rm B}/N_{\rm H}) = -11.66 \pm 0.2$ when a large (+0.54 dex) non-LTE correction is applied. From this, they infer an abundance ratio of N_B/N_{Be} of 17. This is in good agreement with the ratio 10 – 20 predicted by cosmic ray production (Duncan *et al.* 1992; Steigman & Walker 1992). If the ^{9}Be abundance is corrected for the ~ 0.3 dex depletion implied by the stellar models, (no B depletion is predicted for this star) then the abundance ratio is $N_B/N_{Be} = 9$, with a range of 4 – 20 (assuming a 0.3 dex error in the ratio due to uncertainties in the observations, and 0.2 dex due to uncertainties in the depletion). More observations of ^{9}Be in extremely metal poor stars and a better understanding of the effective temperature scale in halo stars are needed to definitively settle the question of the primordial ^{9}Be abundance.

5. Summary

Surface depletion isochrones for ^{6}Li, ^{7}Li and ^{9}Be have been constructed for $Z = 10^{-3}$, 10^{-4} and 10^{-5}, $t = 14$ and 17 Gyr from standard stellar evolution models using the opacities of Iglesias & Rogers (1991) and Kurucz (1991). The isochrones include sub-giant branch evolution and are available in electronic form from the author. The observed detection of ^{6}Li in HD 84937 by SLN93 is compatible with the "standard" model for the production of light elements (SBBN, standard cosmic ray production, no stellar flare production, standard stellar evolution) only if HD 84937 is a sub-giant. The observed parallax rules out this

possibility at the $2.5\,\sigma$ level. A more accurate parallax measurement would serve as a test of the standard model for light element production. The models predict that the abundance of ^{6}Li should be a strong function of effective temperature on the main sequence. Observations of ^{6}Li in a number of main sequence halo stars would be a good test of these models.

Only 8 halo stars with $[\mathrm{O/H}] \leq -1$ have observed ^{9}Be abundances (GGEN92; BK93). The most metal-poor of these, HD 140283 is a relatively cool subgiant. Standard stellar evolution models predict that ^{9}Be is depleted in this star, by ~ 0.3 dex (for $T_{\rm eff} = 5640$ K), implying a protostellar ^{9}Be abundance of $\log(N_{\rm Be}/N_{\rm H}) = -12.54$ (GGEN92; BK93). The exact amount of ^{9}Be depletion is very sensitive to the effective temperature. Ryan *et al.* (1992) determined a lower ^{9}Be abundance (and higher $T_{\rm eff}$). If we use the results of GGEN92 and BK93 then revising the abundance upward changes the oxygen-beryllium relation, suggesting a plateau in the beryllium abundance. This is incompatible with standard cosmic ray production and SBBN. An increase in the observed effective temperature of HD 140283 by ~ 100 K (as suggested by King 1993) or the use of the Ryan *et al.* (1992) abundance resolves this discrepancy. It is clear that an accurate effective temperature and $\log g$ (critical in determining O and Be abundances) scales for halo stars are crucial for our understanding of the origin of the light elements.

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